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TITANIUM SANDWICH AIRFRAME STRUCTURE
Volume 1: Program Overview

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Benecor, Incorporated

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Final Report

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14. ABSTRACT
Mechanical properties of laser welded titanium (Grade 9, Ti3Al2.5V) honeycomb core have been developed by testing for density, compression, and plate shear using the applicable ASTM test standards. Additionally, panels were fabricated employing the same titanium honeycomb core material, constructed using bismaleimide (BMI) face sheets and a cyanate esther film adhesive. These panels were tested using applicable ASTM standards for tension and beam flexure of bonded panels. Much of the core in this study was coated with zirconium for improved adhesion performance. All testing was performed at ‘ambient’ room/storage conditions. The panels were bonded using a proprietary bonding procedure that is ITAR-restricted. The procedure used in preparing the specimens is also discussed per the respective ASTM standards. Results are reported in the Final Report document. Five CDs make up the data volumes and contain the data sheets and failure plots.

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SUMMARY

One of the larger hurdles to bringing new materials to marketplace applications is the presence of useful data. In the case of aerospace applications, the existence of a database that contains mechanical properties of titanium honeycomb core was vacant. Thus, it is normal for an aircraft manufacturer, or weapons developer, to invest in a study, develop the data and because they have paid for and own the data, there is a competitive advantage to keeping this data as proprietary.

The Government's Robust Composite Sandwich Structures (ROCSS) program[2], along with a limited internal study performed by Lockheed Martin, served as a motivator for the US Government to invest in the testing of Benecor's laser welded titanium honeycomb core. Their studies indicated that Benecor's patented laser welding system could provide a stable, strong, cost-effective titanium honeycomb core product. Therefore, the primary activities of this effort were as follows:

- Develop a performance database of the advanced titanium honeycomb core would be developed to assist in certification of these materials for aerospace system application
- Modes and mechanisms of failure would be characterized.
- Data would be developed in collaboration with an independent third party test organization and shared with the aerospace industry.

Through the 4 years of this program, Benecor has published data and performed the testing per the plan submitted to the US Government customer/sponsor. Technical coordination was provided by Wright-Patterson Air Force Base. Wright Patterson's William G. Baron was the Government Project Manager. The timely assistance of Lockheed Martin and Northrop Grumman, as consultative partners, has played a significant role in the execution of this program.

The configurations that were tested were specifically requested by those same partners with the agreement of the US Government customer/sponsor. The development and publication of the Grade 9 Titanium laser welded honeycomb core mechanical properties is the end objective and, by this result, this program should be considered a successful one. This report and the data volumes provide mechanical properties of Titanium 3Al 2.5V that will be useful for aerospace, military and other commercial applications.

This report is written in two volumes. Volume 1 comprises the development information that should allow the reader to understand how the testing has been performed and the summary material properties which were the project objective. Volume 2 is a Data Volume that contains data sheets, failure plots and failure mode characterization for the tests. This volume contains all of the information that supports and meets the requirements of the respective ASTM test reporting protocols.

1.0 INTRODUCTION

Honeycomb core materials have long been understood to provide lightweight yet sturdy structural solutions to aircraft and other applications. When bonded between face sheets, a honeycomb panel has been demonstrated[1] repeatedly to provide a rigid, lightweight and effective structural element. This has a particularly strong impact on aircraft, but in this age of fuel concerns, the potential applications for lightweight structural elements could prove to have limitless potential in other transportation industries such as automobiles, trucks, trains, etc.

While there are competing materials on the marketplace for core materials, including aluminum, steel and manmade materials like Nomex and Phenolics, titanium's presence is traditionally cut relatively short because of the expense associated with titanium. Even aircraft manufacturers shy away from titanium and employ the materials mentioned above while accepting the known performance issues of additional weight, corrosion and increased operation costs[2] stemming largely from repairing and replacing core-integrated parts.

Lockheed Martin and Wright Patterson Air Force Base (WPAFB) studied Benecor's titanium core and documented[2] relative improved performances of the Benecor laser welded titanium honeycomb core over other titanium honeycomb core already on the market, produced using 'legacy' production methods including resistance welding and bonding strategies. Key to this new technology was stronger node strength, thus strength to weight ratios would increase.

There was strong interest in the deployment of Benecor's laser welded titanium honeycomb core. With the support of several defense contractors an effort commenced to secure funding for the development of this database.

The mechanical properties would be developed using ASTM standards to assure uniformity and conformity across most industries of interest. Phase 1 of this program involves the density, compression and plate shear testing of the bare core. During the development, the data would be housed in a secure database and, upon completion of testing; the properties would be published and available for use by any and all, including aerospace and military applications.

Critical to the successful transition from development to production[4] is that the development program has sufficient definition of a mission. The Joint Strike Fighter (JSF) program is in such a transitional phase and timely releasing of mechanical properties started in 2008. However, as in most honeycomb core applications, the materials are going to be bonded or brazed into panels. This is the case for JSF applications and, thus, there is an interest to characterize the core performance when bonded. To that end, phase 2 of this program involves two mechanical properties test protocols, beam flexure and tensile tests on bonded panels, per the applicable ASTM standards.

The panels of phase 2 are fabricated using BMI face sheets and a cynate ester adhesive. Bonding specifications that are used were derived from military applicable system approaches for bonding

composite panels. Development costs have been borne by the government, yet the application is still broad enough that other companies may benefit from this database.

Benecor and Lockheed Martin worked to develop a coating that would enhance adhesive performance of the titanium core. Most of the core tested in this program was coated with this proprietary coating. (Exceptions will be noted.)

Testing per the appropriate ASTM standards was performed by Kansas State University's Mechanical and Nuclear Engineering Test Laboratory under the direction of Kevin Lease, PhD and Elizabeth Frink, PhD graduate student. Engineering students were employed to provide testing support and include Ryan Parsons, Andrew Dickson and Scott Hand under the supervision of Dr. Lease and Ms. Frink.

2.0 MATERIAL DESCRIPTION

The normal presentation of test results, per the referenced ASTM test standards, would call for describing the material in each test program. However, because this program is focused on one specific technology (laser welding), one material, Grade 9 Titanium per ASTM B265, it is prudent to describe the materials in one section and recognize that this description represents all tested materials in this report.

2.1. The Honeycomb Core Manufacturing Process

Laser welded honeycomb core is fabricated using Benecor's patented laser welding process. A strip of foil is laid on a flat surface. Another strip is placed on top of it and, using lasers, the two sheets are welded together. The placement of the welds will influence the cell size. It is also possible to influence cell shape, too, which will impact the mechanical properties of the core. This process can be used on any metallic foils that are weld-able. The welds are placed in such a way that does not allow the weld to go through more than the top two layers of foil.

This process of laying a sheet of foil and welding the sheets at pre-determined intervals is repeated until enough sheets have been laid/welded to allow, upon expansion, to arrive at the desired final size of the honeycomb core blanket.

The HOBE (honeycomb before expansion) is then sliced laterally across the block at a dimension that defines the thickness of the honeycomb core blanket. The method for slicing the HOBE varies depending on the accuracy (tolerance) desired for the application.

Once the core has been sliced to define thickness, the core is manually pinned on both sides of the HOBE slab. The pinned slab is then stretched far enough to arrive at the final cell shape (presumably square, though Benecor does produce different cell geometries). Final trimming of the blanket brings the core to its final 'required' size.

There are no adhesives used in the laser welded core production method. The development of alpha-case oxides typically associated with welding titanium is minimized by the infiltration of Argon gas during the welding process.

2.2. Test Core

The core used in this test program is Grade 9 (Ti 3Al 2.5V) Titanium. It has been laser welded using the process described above.

HOBEs were cut to final thickness employing an Electrical Discharge Machining (EDM). The precision associated with using the EDM results in better surfaces for bonding the core in panels (or platens in the case of plate shear testing). Core height variation could negatively impact bonding strength. There is less core height variation when the slab is cut using an EDM.

Table 1 lists each block welded for the JSF-interest honeycomb core and welding completion dates. Material certifications are maintained by Benecor as part of the quality system requirements.

Table 1: Welded Block Number and Welding Completion Dates

Config.	Cell Size/ Foil Thickness	Nom. Density	Block No / Weld Date				
A	0.108	5.61	3131	3552	3400	3402	3404
	0.001		Und*	9/6/2007	8/25/2006	9/5/2006	10/11/2006
A	0.108	5.61	4136	4290	4294	4296	
	0.001		10/17/2007	2/12/2008	3/20/2008	3/20/2008	
B	0.125	4.78	3406	3408	3410	3412	3414
	0.001		8/20/2007	8/22/2007	8/27/2007	8/28/2007	9/19/2007
D	0.108	8.41	3426	3428	3430	3432	3434
	0.0015		10/22/2007	10/22/2007	10/30/2007	11/1/2007	10/30/2007
E	0.125	7.17	3436	3438	3440	3442	3444
	0.0015		11/21/2007	11/21/2007	11/6/2007	11/20/2007	11/27/2007
G	0.125	9.56	3456	3458	3460	3462	3464
	0.108		2/5/2007	2/5/2007	2/19/2007	6/27/2007	6/27/2007
Q	0.108	11.21	4196	4408	4410	4412	4414
	0.002		und	5/1/2008	5/1/2008	5/7/2008	8/13/2008
Q	0.108	11.21	4562	5139			
	0.002		8/10/2008	11/9/2009			

*und = undeterminable

2.3. Coating

All of the core employed in this test program was coated with a thin layer of a proprietary coating. This coating is believed to enhance adhesion performance.

2.4. Bonded panels

Phase 2 of this program required that the core be bonded into panels. Then tensile strength and beam flexure tests were performed per the applicable test standards. Panel testing was performed on 0.25-inch, 0.50-inch and 1.00-inch thick core that is bonded into the specimens. (Bare core testing did not employ 1.00-inch thick samples, but instead, tested 0.625-inch specimens.) Total panel thickness adds roughly 0.08-inch to the core thickness due to the two face sheets and adhesive.

The face sheets were fabricated from Cytec’s 5250-4 IM7-G 145/32 (bismaleimide prepreg). They were constructed in a symmetric layup about the mid-plane of 0/-45/+45/0/0/+45/-45/0.

The adhesive used in bonding the panels was Cytec's 2550G. The bonding cycle is restricted from distribution by the Arms Export Control Act. The specification is on loan to Benecor by the vehicle of a proprietary agreement.

Panels and face sheets received Non-Destructive Investigation (NDI) testing prior to fabrication into test specimens. The NDI testing was performed using specifications acquired via proprietary agreements.

2.5. Loading Blocks and Platens

Platens were fabricated for plate shear testing, ASTM C273. Loading blocks were fabricated for tensile testing per ASTM C297. In both cases, the platens and loading blocks were manufactured from 4140 Steel.

2.6. Environmental Conditions

All testing was performed at standard laboratory atmosphere (73+/-5F and 50+/-5% relative humidity). On each data sheet, the temperature and humidity condition of the lab where the testing was performed has been noted.

3.0 METHODS, ASSUMPTIONS AND PROCEDURES

Each subsection of this section will be focused on describing how the testing of the titanium honeycomb core has been performed. The methods, assumptions and procedures section will address the actual requirements as specified in each of the supporting test standard. Once all five standards have been addressed, the report will then proceed with the Results and Discussion where tables of mechanical properties are presented.

The equation systems used to calculate the mechanical properties are presented in this section. The methods for calculating standard deviation, average and coefficient of variation (COV) have been intentionally omitted.

3.1. Density

Density testing has been performed per ASTM C271-05[5]. The material has been described in Material Description, Section **Error! Reference source not found.**.

Blankets of titanium honeycomb core were measured and weighed. Calipers were used for the measurement of the core. The calipers used were digital calipers made by TESA, Inc, serial number 3A1320601. The core blankets were weighed, in grams, using a Setra EL-410D scale, capacity 410g.

The core specimens are blankets numbered according to their configuration (alphabet), thickness (number) and lot number (number). For example, G205-008 would be a specimen of G configuration; half inch thick (2) and the fifth batch (05). The number after the dash is the identifier of each individual sheet of core, i.e., a serial number.

Measurements and weights were then used to calculate density in pounds per cubic foot using equation 1:

$$d_{ip} = 3.81 \frac{M}{lwt} \tag{1}$$

Where:

d_{ip} = density [lb/ft^3]

M= weight of specimen [grams]

l = measured length of specimen [in.]

w= measured width of specimen [in.]

t = measured thickness of specimen [in.]

Results of the measurement tests are shown in Table 2 of the Results and Discussion section, Section 4.1.

3.2. Compression Testing

Compression testing has been performed per ASTM C365-05[9]. All specimens employed for the compression testing were cut to 3”x 3” coupons using a water cut saw (circular). The blade is a diamond-encrusted blade and the cutting was performed using the water to lubricate. This cutting method was employed for the stabilized specimens too. The specimen thickness was cut from the block using an EDM machine.

For the stabilized compression tests, the specimens were either taken directly from panels that were fabricated for the panel testing (phase 2), tensile and beam flexure, or they were specifically bonded just for the stabilized compression tests using 3M’s AF163-2 and the BMI face sheets. In view that the failure modes should not depend on the bonding scheme, it is not expected that this will influence the results.

There was no environmental conditioning of the core. Laboratory conditions are shown with the test results’ data sheets in the data volumes.

Compression properties are calculated using the equations 2 and 3, as prescribed in the standard[9].

$$F_z^{fcu} = {}^{P_{\max}}/_{A} \tag{2}$$

Where:

F_z^{fcu} = ultimate flatwise compression strength [psi]

P_{max}= ultimate force prior to failure [lb]

A = cross-sectional area [in^2]

The 2% Deflection Stress is calculated as follows:

$$\sigma_z^{fc0.02} = P_{0.02}/\text{ A} \tag{3}$$

Where:

$\sigma_z^{fc0.02}$ = ultimate flatwise compressive strength [psi]

$P_{0.02}$ = applied force corresponding to $\delta_{0.02}$ [lbf]

$\delta_{0.02}$ = recorded deflection value such that ${}^{\delta}/_{t}$ is closest to 0.02, and

t = measured thickness of the core specimen prior to loading [in.]

Compressive modulus is calculated using equation 4:

$$E_z^{fc} = ((P_{0.003} - P_{0.001}) \cdot t) \,/\, ((\delta_{0.003} - \delta_{0.001}) \cdot A) \quad (4)$$

Where:

E_z^{fc} = core flatwise compressive chord modulus [psi]

$P_{0.003}$ = applied force corresponding to [lbf]

$P_{0.001}$ = applied force corresponding to [lbf]

$\delta_{0.003}$ = recorded deflection value such that δ/t is closest to 0.003, and

$\delta_{0.001}$ = recorded deflection value such that δ/t is closest to 0.001.

Bare core and stabilized compression test results are presented in the Results and Discussion Section as well as the compression data volume. Figure 1, shows a bare core specimen post compression testing. Figure 2 shows the stabilized core specimen after testing.

Figure 1: Uncoated Titanium Honeycomb Core after Compression Test

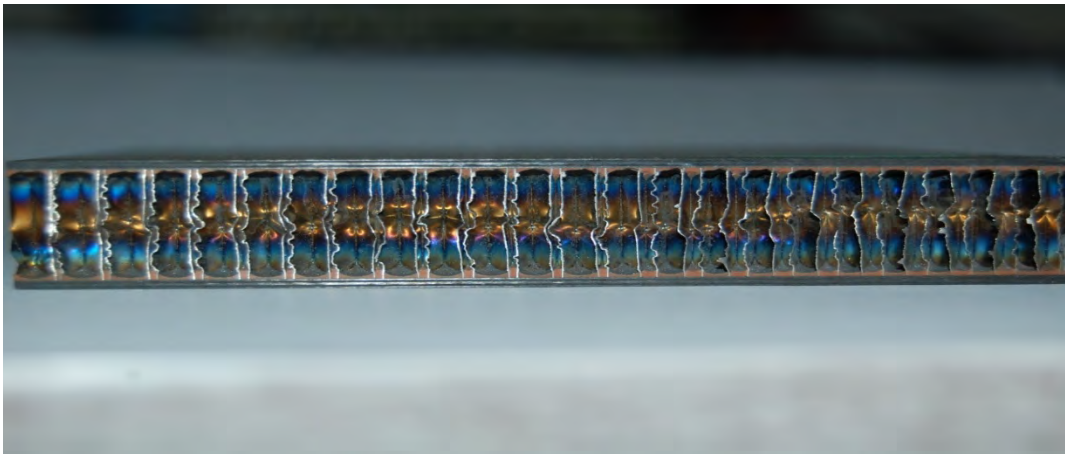


Figure 2: Stabilized Compression Test Specimen Post-Testing

3.3. Plate Shear Testing

Core shear properties are fundamental properties that are used in the design of sandwich panels. Plate Shear testing has been performed according to ASTM C 273-00[7]. This test method provides a standard for obtaining sandwich core shear data for quality control, acceptance specification testing, sandwich design, and research and development. The material is described in the Materials Description section.

All specimens were cut to final specimen size using a water cut saw which employs a diamond-encrusted blade under running water to lubricate. The specimen size varied, in accordance with the test standard to reflect the various thicknesses of the specimens under consideration.

0.25 inch: 2” x 3”

0.50 inch: 2” x 6”

0.625 inch: 2” x 7.5”

Specimen sizes are shown for each batch as presented in the data sheets of the individual and batch test results in the appendix. The sizes shown above are nominal but have been measured and posted using calipers as described in the Material Description to the required accuracy.

The specimens were bonded to steel platens as shown in Figure 3. Those platens were fabricated in accordance with the test standard, using cold rolled steel 4140. Bonding was performed using 3M’s AF163-2 adhesive.

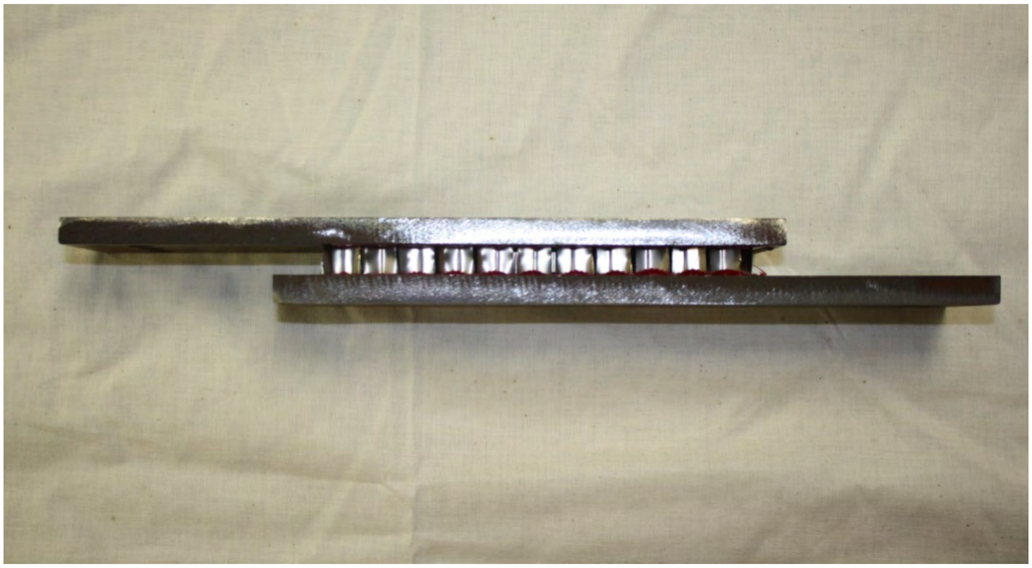


Figure 3: Shear Specimens Bonded To Steel Platens

As is standard in honeycomb core testing, the testing of the core was performed in the ribbon and expansion orientations. However, in order to better characterize the material, a third orientation which is being called “angle” was also included in the test protocol. The angle orientation is created by cutting the specimen 45° off the ribbon (or expansion) orientations, as shown in Figure 4. The ribbon direction of the core is along the bottom of the figure. The larger cells on that figure are the ‘pinning and stretching’ region of the core blanket that is trimmed off of the final product.

Figure 4: Angle Orientation for Shear Tests

Shear stress is calculated using equation 5 below:

$$\tau = \frac{P}{Lb} \quad (5)$$

Where:

$\tau = core\ shear\ Stress$ [psi]

P = load on specimen [lb]

L = length of specimen [inch]

b = width of specimen [inch].

The ultimate shear strength is obtained using equation 5 when P equals the maximum load and the shear yield strength where P equals the yield load. For core materials that yield more that 2% strain, use the 2% offset method for the yield strength.

Shear modulus is calculated using equation 6 below:

$$G = \frac{St}{Lb} \tag{6}$$

Where:

G = core shear modulus [psi]

S = $\frac{\Delta P}{\Delta u}$, slope of initial portion of load-deflection curve, [lb/in.]

u = displacement of loading plates [in.]

t = thickness of core [in.]

Shear stress test results for 3 core orientations are presented in the Results and Discussion section, Table 5, as well as the data volume of this report. Failure plots and data sheets for all of the shear testing are provided in the data volumes.

3.4. Flatwise Tensile Testing

In a sandwich panel, core-to-facing bond integrity is necessary to maintain facing stability and permit load transfer between the facings and core. The flatwise tensile testing method can be used to provide information on the strength and quality of core-to-facing bonds. This testing has been performed in accordance with ASTM C297-04[4]. The material is described in the Materials Description section.

This testing utilized bonded panels, bonded per the process specification of reference 5. Specimens were cut into 2” x 2” panels and then bonded to loading blocks using AF163-2 adhesive. A typical tensile test specimen is shown in Figures 5, before and after tensile testing.

Ultimate tensile strength is calculated as follows:

$$F_z^{ftu} = P_{max} / \mathrm{A} \tag{7}$$

Where:

F_z^{ftu} = ultimate flatwise tensile strength [psi],

P_{max} = ultimate force prior to failure [lbf],

A = cross-sectional area [in^2].

Tensile test results are shown in the summary table of Results and Discussion, Flatwise Tensile Testing and in the data volumes.

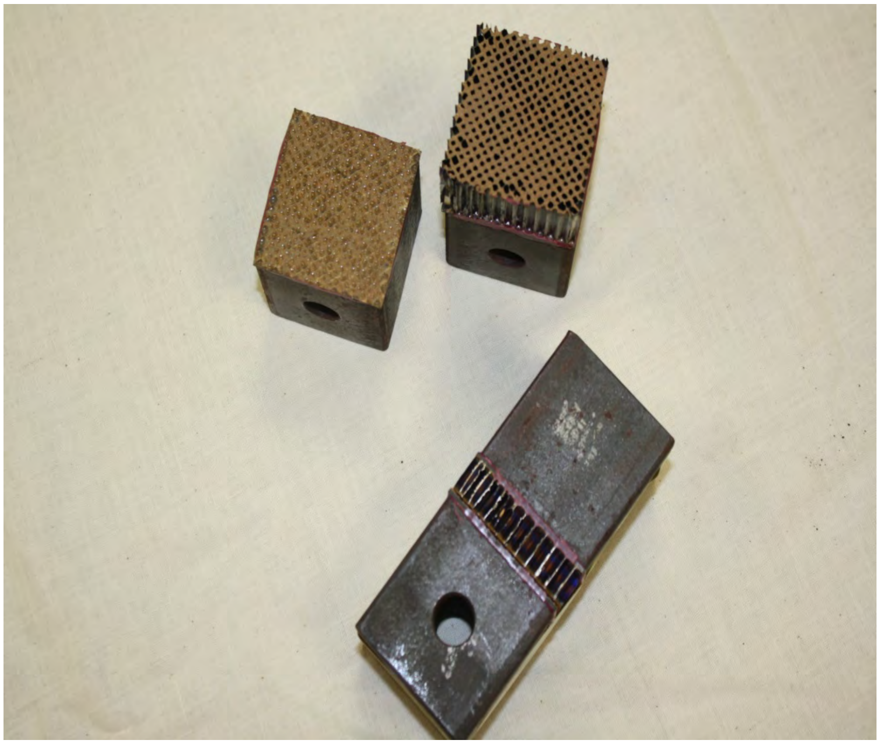


Figure 5: Tensile Test Specimens Pre- and Post- Testing

3.5. Beam Flexural Properties

Flexure tests on flat sandwich construction may be conducted to determine the sandwich flexural stiffness, the core shear strength and shear modulus, or the facings compressive and tensile strengths. Tests to evaluate core shear strength may also be used to evaluate core-to-facing bonds. This testing has been performed in accordance with ASTM C393-06[10]. The material is described in the Materials Description section.

Bonded panels were fabricated in accordance with the procedures provided in reference 5. Panels were cut using a watercut saw that uses a diamond-encrusted circular saw blade, wet cut (water) for lubrication and heat dissipation.

Specimen size varied, in part, because of material planning and availability. Due to adhesive failures in phase 1, less core material was available for panel fabrication and subsequent panel testing. Review of the flexural properties standard indicated that the flexural stiffness and core shear modulus were not impacted by length of the specimens. The last two versions of the standard do allow for 'non-standard' specimen sizing likely because some of the mechanical properties are not specimen size dependent. The latest standard defines the standard specimen size as 3"x8" and anything else is non-standard. Non-standard specimens can be used as long as they are identified as such.

Testing was performed using two-point, third point loading as shown in Figure 2 of reference 10. Core shear stress is calculated using equation 8:

$$\tau = \frac{P_{ult}}{(d+c)b} \tag{8}$$

Where:

τ = core shear stress [psi]

P_{ult} = load [lb]

d = sandwich thickness [in.]

c = core thickness [in.]

b = sandwich width [in.]

Flexural stiffness is calculated using equation 9:

$$D = \frac{E\left(d^3 - c^3\right)b}{12} \tag{9}$$

Where:

D = flexural stiffness (lb-in^2)

E = facing modulus (psi)

d = sandwich thickness (in.)

c = core thickness (in.)

b = sandwich width (in.)

And Core Shear Modulus is calculated using equation 10:

$$G = D \quad \frac{(d-2t)}{(\,(d-t)^2 * b)} \tag{10}$$

Where G = cores shear modulus (psi).

The facing modulus was determined by performing tests on the face sheet material per ASTM D7249[10]. It was determined to be 1.45E+07 psi.

Figure 1 shows side views of beam flexure specimens, before and after testing. Note that on the right hand side of the tested (lower) specimen, the adhesive has failed. The dark coloration near the facings on the core is the coating applied to enhance adhesive performance.

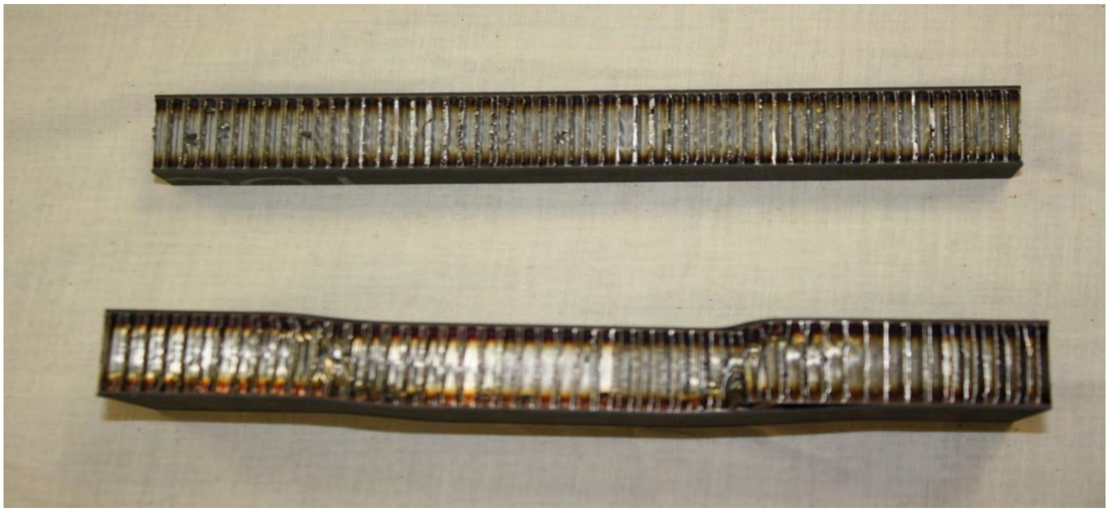


Figure 6: Beam Flexure Test Specimens Pre- and Post- Testing

For each of the tests that were performed, the failure mode and location has been described and mapped, respectively. The failure modes varied throughout the testing and are best left with the descriptions presented in the respective data sheets for the individual specimen tests.

4.0 RESULTS AND DISCUSSION

Data presented in these sections are, as shown, the average, standard deviation and the COV as required by the ASTM. Aerospace applications will tend to perform additional calculations to provide A-basis or B-basis and other percent confidence levels. The information provided for this report will allow for those additional calculations. The ASTM test requirements call for the data that is being presented in this report.

4.1. Density Results

Measurements for length, width and thickness were combined with the specimen weight of at least four batches of each configuration of honeycomb core. Complete data is in the Data Volume. Table 2 summarizes the six configurations' density measurements.

Table 2: Core Density Measurements

Nom. Density [lb/ft^3]	Average [lb/ft^3]	STD DEV	COV %
4.78	**5.071**	0.051	1.014
5.61	**5.366**	0.158	2.952
7.17	**7.169**	0.149	2.081
8.41	**8.355**	0.063	0.756
9.56	**10.076**	0.521	5.171
11.21	**10.929**	0.412	3.675

The variation in density for the core can be attributed to foil thickness and cell size variation. Benecor's specification cites a $\pm 10\%$ cell size variation allowable. However, process capability studies performed by Benecor cite cpk (process capability) values of four or more for a 7.5% tolerance band. This basically suggests that fewer than one cell out of 10,000 will be out of tolerance. The foil suppliers do have a tolerance band of $\pm 10\%$ for foil thickness which is directly translatable into a density impact on the core.

4.2. Compression Testing Results

Table 3 summarizes the bare core compression testing performed for six configurations of honeycomb core. This table, by nominal density and specimen thickness, lists the compressive strength, core compressive modulus, standard deviation and COV for the 6 configurations.

Figure 87 shows a typical compression failure plot for the titanium core, density of 5.61 lb/ft^3. Figure 98 illustrates the energy absorption properties of the same titanium core. The typical crush performance of metallic honeycomb core is once again illustrated by the obvious peak early in the crush stroke followed by the relatively horizontal 'constant load' region of the failure plot.

Data sheets and failure plots for each of the tests that have been performed for the bare core test program are posted in the data volumes of this report.

Table 3: Compressive Mechanical Properties of Laser Welded Titanium Honeycomb Core

	Thickness	**0.25 inch**		**0.50 inch**		**0.625 inch**	
Nom. Density		**Ult. Comp. Strength**	**Core Comp. Modulus**	**Ult. Comp. Strength**	**Core Comp. Modulus**	**Ult. Comp. Strength**	**Core Comp. Modulus**
[lb/ft^3]		[psi]	[ksi]	[psi]	[ksi]	[psi]	[ksi]
4.78	Average	611.03	55.99	580.72	71.14	588.23	81.47
	Std Dev	40.53	5.10	46.04	10.43	49.22	7.68
	COV*	0.07	0.09	0.08	0.15	0.08	0.09
5.61	Average	754.63	73.39	731.99	94.10	721.23	98.11
	Std Dev	53.77	11.25	54.16	10.56	47.75	12.01
	COV	0.07	0.15	0.07	0.11	0.07	0.12
7.17	Average	1306.61	111.30	1260.03	149.04	1240.74	148.19
	Std Dev	67.74	5.80	54.38	14.83	51.83	22.23
	COV	0.05	0.05	0.04	0.10	0.04	0.15
8.41	Average	1611.63	169.89	1565.39	218.08	1554.84	224.16
	Std Dev	174.25	22.85	162.44	30.83	96.17	35.28
	COV	0.11	0.13	0.10	0.14	0.06	0.16
9.56	Average	1756.12	145.68	1697.12	213.75	1706.94	230.24
	Std Dev	123.52	12.59	104.39	20.09	116.76	14.89
	COV	0.07	0.09	0.06	0.09	0.07	0.06
11.21	Average	2241.98	183.61	2180.95	277.59	2192.59	312.82
	Std Dev	171.65	15.82	161.34	21.65	164.89	14.96
	COV	0.08	0.09	0.07	0.08	0.08	0.05

*Note that COV are decimals and not percentages throughout this table.

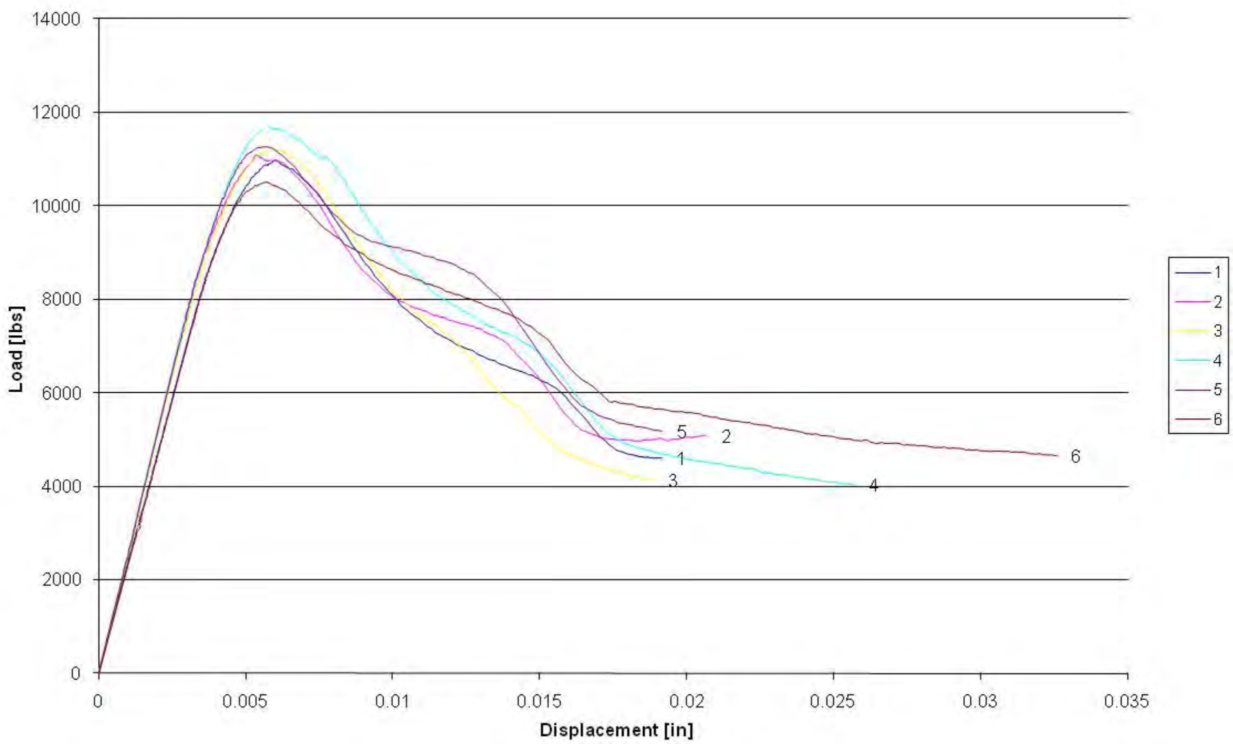


Figure 7: Compression Failure Plot: 5.61 Lb/Ft3 Titanium Honeycomb Core

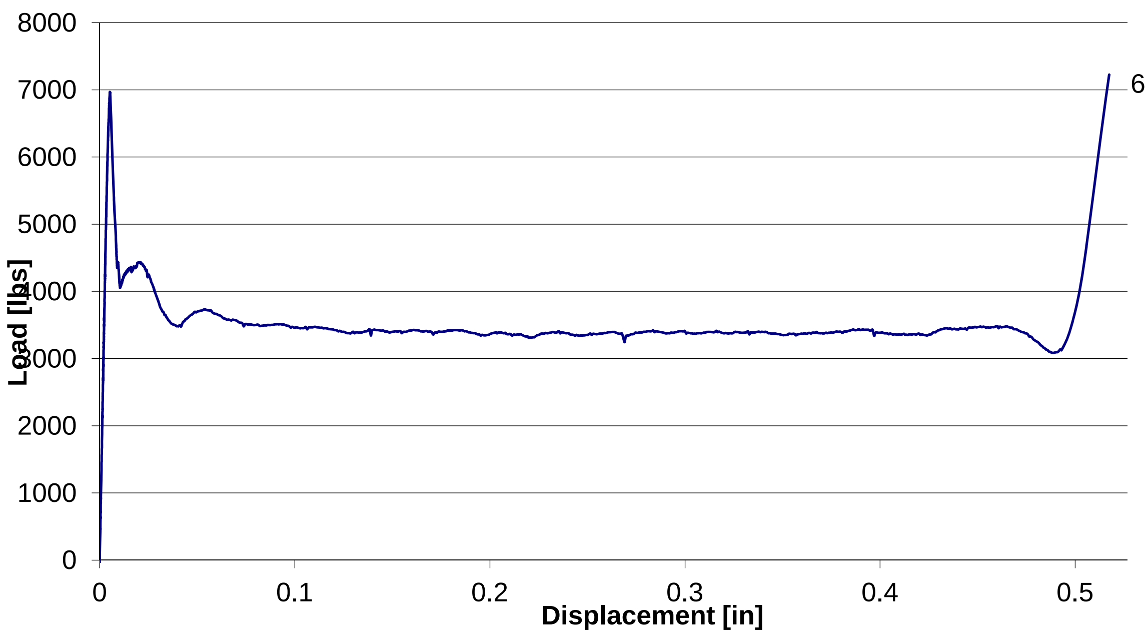


Figure 8: Energy Absorption Plot: 5.61 Lb/Ft3 Titanium Honeycomb Core

Table 4 shows the results of stabilized compression tests. The stabilized tests were conducted on panels constructed using the same bonding protocol as was employed for phase 2 panel testing. Future updates in stabilized core testing may use different adhesives to bond to the face plate but this should have no impact on the failure mode and thus, the integrity of the data when compared to the data produced during this round of testing. "No Data" means that there was no available core or panel to complete this testing.

Table 4: Stabilized Compression Test Results for Titanium Honeycomb Core

	Thickness	**0.25 inch**		**0.50 inch**	
Nom. Density		**Ult. Comp. Strength**	**Core Comp. Modulus**	**Ult. Comp. Strength**	**Core Comp. Modulus**
[lb/ft^3]		[psi]	[ksi]	[psi]	[ksi]
4.78	Average	NO DATA		601.4	70.1
	Std Dev			21.24	4.54
	COV*			0.035	0.065
5.61	Average	794.5	72.96	795.9	89.7
	Std Dev	55.88	12.63	26.76	11
	COV	0.07	0.173	0.030	0.123
7.17	Average	1377.5	123.84	1287.4	156.49
	Std Dev	111.24	19.43	56.37	17.94
	COV	0.081	0.157	0.044	0.115
8.41	Average	1773.3	149.63	1670.9	192.83
	Std Dev	83.37	10.44	55.81	17.35
	COV	0.047	0.07	0.033	0.09
9.56	Average	1934.5	156.84	1794.2	222.9
	Std Dev	69.96	11.6	71.74	30.14
	COV	0.036	0.074	0.040	0.135
11.21	Average	2447.5	158.03	2339.9	276
	Std Dev	77.92	12.07	54.79	50.85
	COV	0.032	0.076	0.023	0.184

*Note: COV is in decimal form, not percentage, throughout this table.

4.3. Plate Shear Testing Results

Table 5 summarizes the plate shear testing performed for the six core configurations. This data is shown for the 'traditional' cases of ribbon and expansion but also includes the 'angle' configuration which, as a reminder, is the orientation 45° from the ribbon (or expansion) core orientation, as was shown in Figure 4.

Table 5: Plate Shear Strength and Core Modulus for Titanium Core

Density lb/ft^3	Core Thickness [in.]		SHEAR STRENGTH [psi] / CORE MODULUS [ksi]					
			RIBBON		TRANSVERSE		ANGLE	
4.78	0.25	AVERAGE	**637.58**	**35.46**	**541.95**	**24.73**	**512.23**	**28.45**
		STD DEV	97.20	6.37	23.50	3.78	18.10	4.72
		COV	0.15	0.18	0.04	27.61	0.04	0.17
	0.50	AVERAGE	**514.36**	**32.44**	**418.34**	**21.94**	**427.97**	**25.55**
		STD DEV	20.82	6.11	16.77	1.81	10.90	4.47
		COV	0.04	0.19	0.04	0.08	0.03	0.17
	0.625	AVERAGE	**505.33**	**32.55**	**411.98**	**22.48**	**434.44**	**28.06**
		STD DEV	22.99	2.80	14.38	2.91	15.48	3.15
		COV	0.05	0.09	0.03	0.13	0.04	0.11
5.61	0.25	AVERAGE	**666.13**	**35.68**	**615.86**	**30.16**	**570.93**	**33.18**
		STD DEV	29.66	3.44	27.30	4.81	26.54	4.81
		COV	0.04	0.10	0.04	0.16	0.05	0.14
	0.50	AVERAGE	**599.68**	**47.53**	**504.59**	**29.99**	**518.48**	**32.70**
		STD DEV	48.48	36877.84	32.00	4.92	20.68	3.71
		COV	0.08	0.78	0.06	0.16	0.04	0.11
	0.625	AVERAGE	**509.57**	**33.10**	**599.88**	**44.53**	**497.96**	**31.85**
		STD DEV	25.18	3.42	35.66	6.73	29.44	8.31
		COV	0.05	0.10	0.06	0.15	0.06	0.26
7.17	0.25	AVERAGE	**1001.45**	**42.03**	**920.87**	**39.29**	**787.96**	**40.64**
		STD DEV	58.52	3.52	39.02	4.22	30.21	4.43
		COV	0.06	0.08	0.04	0.11	0.04	0.11
	0.50	AVERAGE	**837.13**	**55.83**	**789.64**	**47.40**	**692.91**	**46.94**
		STD DEV	31.96	9.28	46.58	9.80	22.47	4.08
		COV	0.04	0.17	0.06	0.21	0.03	0.09
	0.625	AVERAGE	**805.27**	**61.36**	**741.27**	**49.02**	**667.65**	**53.92**
		STD DEV	53.52	15.25	23.21	3.40	19.56	7,82
		COV	0.07	0.25	0.03	0.07	0.03	0.15

*Note that the COV is in decimal form and not percentage throughout this table.

Table 5: Plate Shear Strength and Core Modulus for Titanium Core (continued)

Density lb/ft^3	Core Thickness [in.]		SHEAR STRENGTH [psi] / CORE MODULUS [ksi]					
			RIBBON		TRANSVERSE		ANGLE	
8.41	0.25	AVERAGE	**1161.78**	**51.77**	**1064.22**	**45.85**	**912.12**	**48.95**
		STD DEV	68.35	6.32	40.78	4.30	37.01	4.80
		COV	0.06	0.12	0.04	0.09	0.04	0.10
	0.50	AVERAGE	**984.81**	**72.14**	**928.46**	**68.89**	**800.88**	**65.54**
		STD DEV	44.14	9.23	70.71	13.02	19.16	8.38
		COV	0.04	0.13	0.08	0.19	0.02	0.13
	0.625	AVERAGE	**915.72**	**78.58**	**867.49**	**67.47**	**772.53**	**79.87**
		STD DEV	112.94	8.88	43.51	4.92	21.32	13.08
		COV	0.12	0.11	0.05	0.07	0.03	0.16
9.56	0.25	AVERAGE	**1077.58**	**51.22**	**1093.30**	**53.51**	**889.75**	**52.85**
		STD DEV	28.78	7.36	43.43	10.37	28.29	6.91
		COV	0.03	0.14	0.04	0.19	0.03	0.13
	0.50	AVERAGE	**947.60**	**75.76**	**915.84**	**77.70**	**787.40**	**79.94**
		STD DEV	45.93	7.56	44.00	9.50	30.36	14.85
		COV	0.05	0.10	0.05	0.12	0.04	0.19
	0.625	AVERAGE	**875.42**	**130.05**	**936.57**	**210.89**	**726.86**	**95.85**
		STD DEV	73.72	52.85	33.09	84.80	17.01	7.78
		COV	0.08	0.41	0.04	0.40	0.02	0.08
11.21	0.25	AVERAGE	**1431.01**	**53.59**	**1211.95**	**46.39**	**1027.82**	**50.64**
		STD DEV	68.48	5.14	105.49	3.74	58.46	12.63
		COV	0.05	0.10	0.09	0.08	0.06	0.25
	0.50	AVERAGE	**1197.82**	**147.93**	**1057.43**	**117.72**	**938.23**	**92.80**
		STD DEV	130.85	80.49	61.41	55.59	45.94	33.73
		COV	0.11	0.54	0.06	0.47	0.05	0.36
	0.625	AVERAGE	NO DATA		**1145.88**	**119.30**	**938.35**	**172.17**
		STD DEV			28.07	24.74	20.60	83.53
		COV			0.02	0.21	0.02	0.49

*Note that the COV is in decimal form and not percentage throughout this table.

It is also noteworthy that the strength of the core in ribbon and transverse core orientations does tend to track together well. See Figure 9 as it shows shear strength performance and also compares it to published aluminum core shear results. Strength performance in the transverse directions is largely a function of the node weld strength. This is an added confirmation that the node weld strength is higher in the laser welded core than expected in other legacy metallic core.

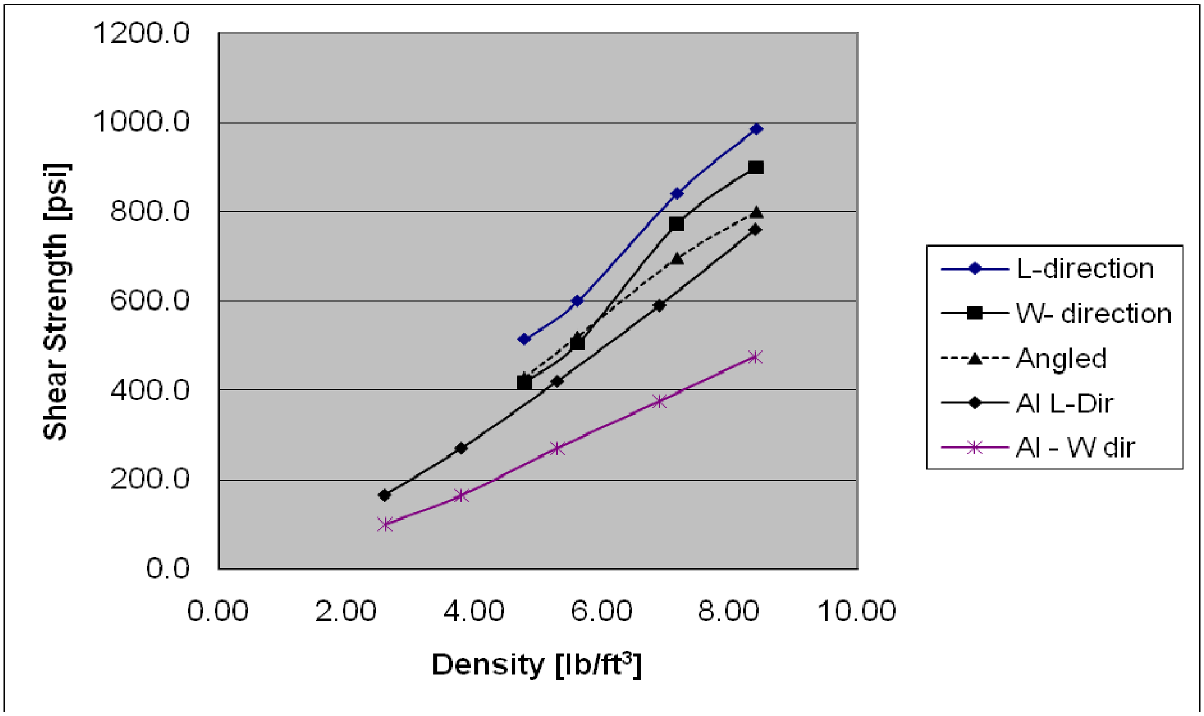


Figure 9: Shear Strength Vs Density of Titanium and Aluminum Honeycomb Core

4.4. Tensile Strength Testing Results

Figure 10 is a failure plot for six specimens, one-half inch thick, 7.17 lb/ft^3 core from one of the five batches tested. This kind of performance was typical of the data. The slopes of the curves are pretty consistent through the different samples. If one thinks of the tensile test in the same context of a spring that is being stretched, that slope represents the spring constant and, in the case of these test specimens, it should reflect the tensile strength of the core.

The peaks of the curves are where the bond between the adhesive and the core is failing in most cases. Failures in the bondline between the loading block and the specimen are not valid for inclusion in the test data. In a few cases, the panel face sheet split as the failure mechanism. The differences shown for start of the linear region of the slope is likely related to the bonding of the face sheet to the core and the bonding of the specimen panel to the loading blocks.

Table 6 lists the results of the tensile testing performed on the bonded panel specimens. Recognizing that the core density is dependent on foil thickness and cell size, smaller cells and thicker foil result in an increase in density. The relationship for these results is that with smaller cells and thicker foils, the bonding surface area is increased. The increased surface area should and does, generally, result in stronger tensile strength performance in this testing series.

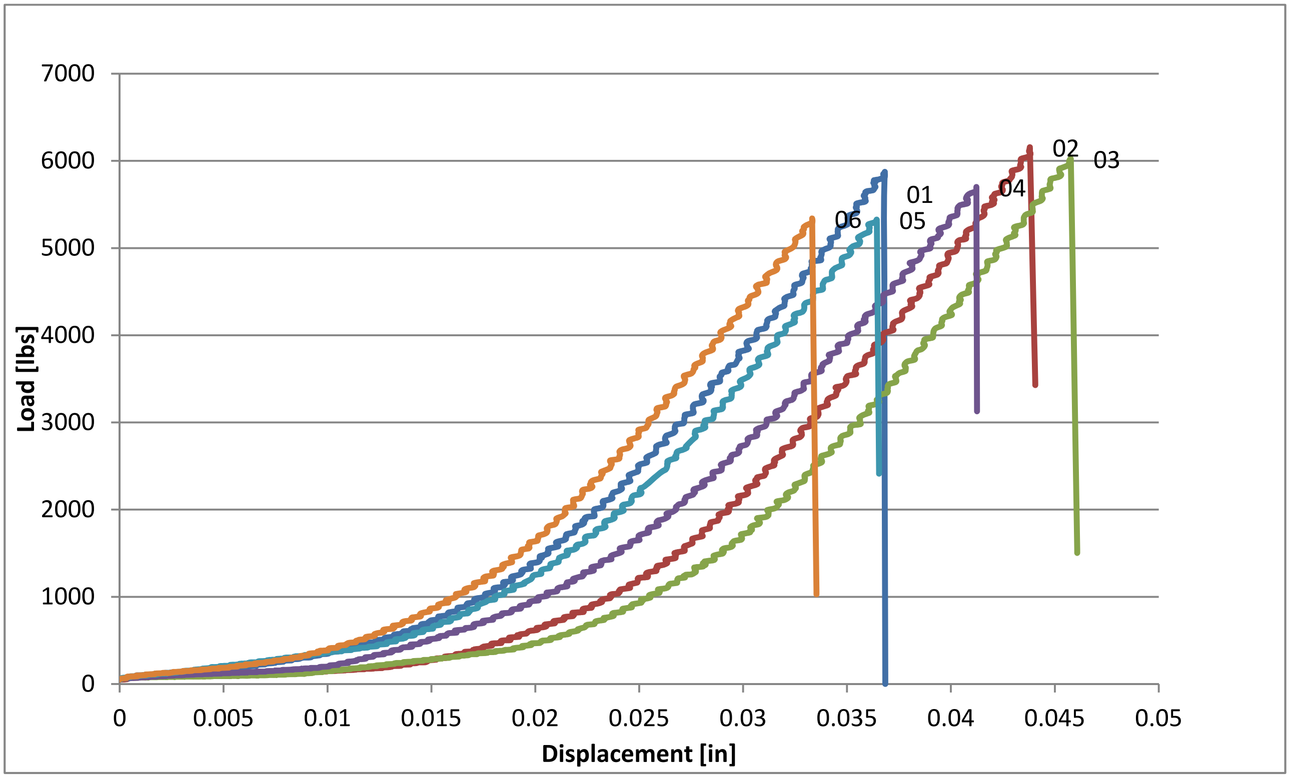


Figure 10: Tensile Test Failure Plot of 7.17lb/Ft3, Half Inch Specimens

Table 6: Tensile Test Results for Titanium Core Bonded To BMI Face Sheets

Density [lb/ft^3]	Avg. Dens.	Core Thickness [in.]	Ult Tens Strength [psi]	Standard Deviation	COV*
4.78	5.07	0.25	1294.6	129.61	0.100
		0.50	1281.7	164.93	0.129
5.61	5.38	0.25	1350.1	289.70	0.215
		0.50	1623.6	200.40	0.123
7.17	7.17	0.25	1208.8	360.75	0.298
		0.50	1511.6	245.01	0.162
		1.00	1385.2	200.80	0.145
8.41	8.35	0.25	1652.0	274.20	0.166
		0.50	1650.6	249.20	0.151
		1.00	1742.8	338.00	0.194
9.56	9.52	0.50	1736.8	167.80	0.097
		1.00	1460.9	130.90	0.090
11.21	10.89	0.50	1872.7	226.80	0.121
		1.00	1638.5	237.50	0.145

*Note that the COV is in decimal form and not percentage throughout this table.

4.5. Beam Flexure Testing Results

A typical beam flexure failure plot for one of the configurations is shown in Figure 11. It shows the behavior for six specimens tested from a single batch. The detailed data information for each test is provided in the data volume along with all failure plots and related test data per the testing standard.

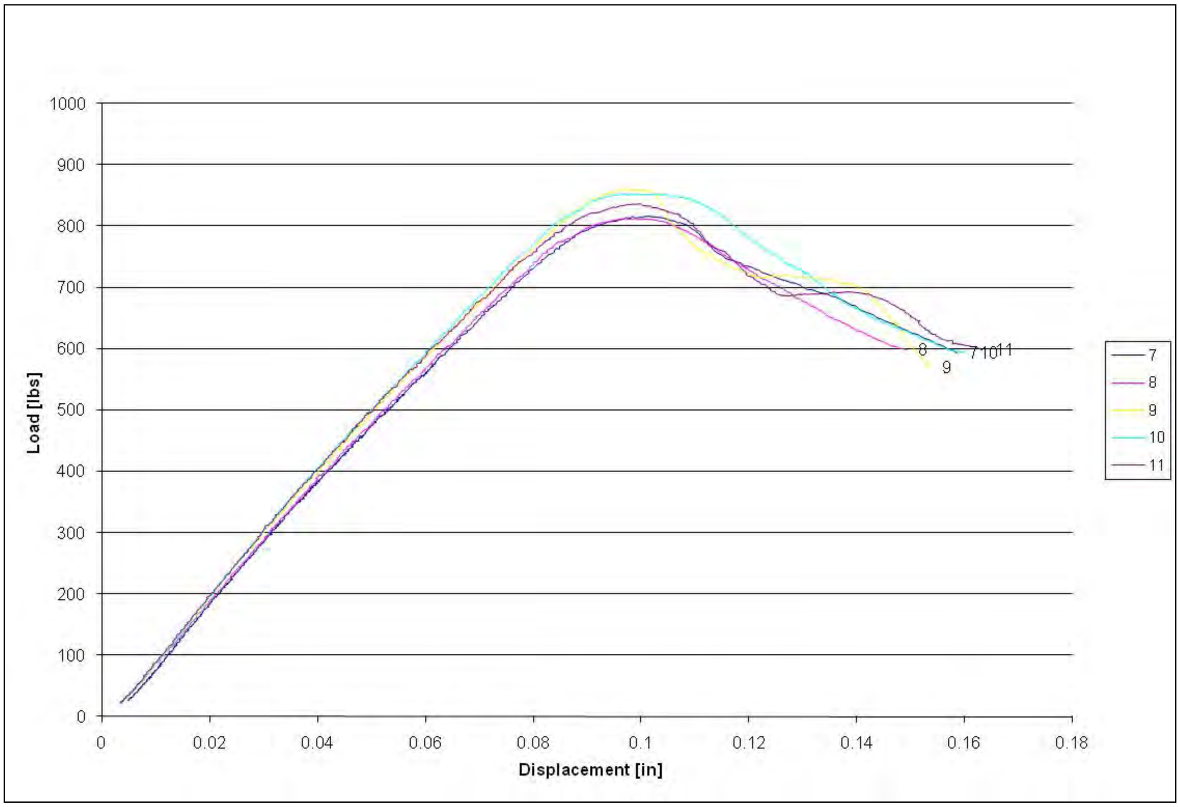


Figure 11: Sample Failure Plot of 8.41 Lb/Ft3, Half-Inch Thick Titanium Core Panel

While not all of the failure plots will show this kind of tight grouping of data, the relatively narrow grouping during the panel's performance in the elastic range of loading is desirable. This kind of tight repetition gives a strong sense for how the material will behave when used in a design and should result in a smaller uncertainty factor (or "knockdown") when allowables are being calculated.

The beam flexure testing results are shown on Table 7. It is interesting to note that a few things are happening at the higher densities. The panel starts to fail before reaching yield more frequently. The test data is also showing that for higher densities, the thicker panels are actually stronger than the thinner panels which were not the case with the less dense systems. Transverse panels continue to test weaker than ribbon, just as they did with bare plate shear tests.

Failure codes are identified for each of the test specimens. Figure 12 is the failure code guide. It also appears in the data volume.

Table 7: Beam Flexure Strength: Grade 9 Ti Core bonded to BMI Facesheets

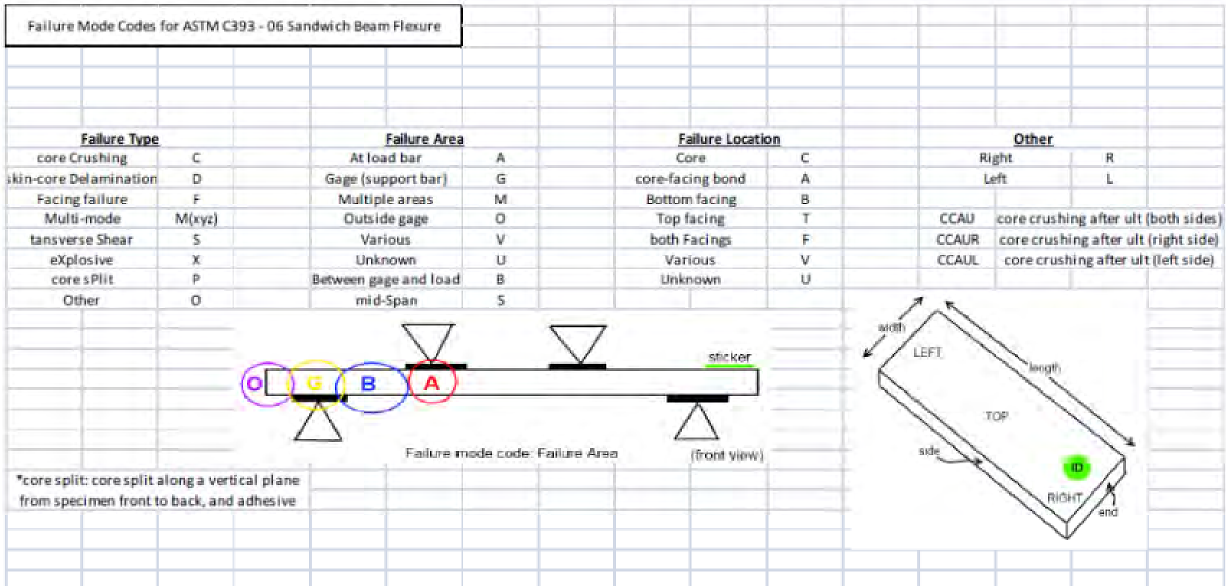
Beam Flexure			**GRADE 9 TI, BMI FACE SHEET, CYTEC ADHESIVE**			
			RIBBON		**TRANSVERSE**	
Density [lb/ft^3]	core thickness [in]		Ult. Strength [psi]	2% Yld Strength [psi]	Ult. Strength [psi]	2% Yld Strength [psi]
4.78	0.25	average	580.2	573.8	490.5	488
		std dev	31.82	29.74	12.66	17.32
		COV*	0.055	0.052	0.026	0.036
	0.50	average	486.1	497.4	394.4	393.1
		std dev	25.96	17.94	23.91	13.97
		COV	0.053	0.036	0.061	0.036
5.61	0.25	average	635.7	599.5	572.3	564.4
		std dev	33.47	118.94	23.91	24.13
		COV	0.058	0.198	0.042	0.043
	0.50	average	509.9	492.7	519.8	**
		std dev	43.41	38.32	5.86	
		COV	0.085	0.078	0.011	
7.17	0.25	average	998.7	948	944.9	852.5
		std dev	122.4	108.6	53.3	53.1
		COV	0.123	0.115	0.056	0.062
	0.50	average	763.9	717.2	740.8	**
		std dev	31.6	55.4	10.0	
		COV	0.041	0.077	0.013	
	1.00	average	747.5	**	661.0	**
		std dev	39.0		16.8	
		COV	0.052		0.025	

*COV is in decimals, not percent, throughout this table.

Table 8: Beam Flexure Strength: Grade 9 Ti Core Bonded to BMI Facesheets (continued)

Beam Flexure			**GRADE 9 TI, BMI FACE SHEET, CYTEC ADHESIVE**			
			RIBBON		**TRANSVERSE**	
Nom. Density [lb/ft^3]	core thickness [in]		Ult. Strength [psi]	2% Yld Strength [psi]	Ult. Strength [psi]	2% Yld Strength [psi]
8.41	0.25	average	1142.9	1113.9	1120.1	1035.9
		std dev	74.8	68.05	44.14	29.02
		COV*	0.065	0.061	0.039	0.028
	0.50	average	953.07	*	869.6	*
		std dev	46.67		19.8	
		COV*	0.049		0.023	
	1.00	average	869.6	*	796.5	*
		std dev	35.88		29.58	
		COV*	0.041		0.025	
9.56	0.50	average	930.4	*	880.6	696.3
		std dev	31.31		19.58	
		COV*	0.041		0.025	
	1.00	average	942.0	*	857.7	*
		std dev	24.5		16.75	
		COV*	0.0		0.019	
11.21	0.50	average	1094.4	*	933.3	725.3
		std dev				
		COV*				
	1.00	average	1241	*	975.7	*
		std dev				
		COV*				

*COV is in decimals, not percent, throughout this table.



Failure Mode Codes for ASTM C393 - 06 Sandwich Beam Flexure

Failure Type		Failure Area		Failure Location		Other	
core Crushing	C	At load bar	A	Core	C	Right	R
skin-core Delamination	D	Gage (support bar)	G	core-facing bond	A	Left	L
Facing failure	F	Multiple areas	M	Bottom facing	B		
Multi-mode	M(xyz)	Outside gage	O	Top facing	T	CCAU	core crushing after ult (both sides)
tansverse Shear	S	Various	V	both Facings	F	CCAUR	core crushing after ult (right side)
eXplosive	X	Unknown	U	Various	V	CCAUL	core crushing after ult (left side)
core sPlit	P	Between gage and load	B	Unknown	U		
Other	O	mid-Span	S				

*core split: core split along a vertical plane from specimen front to back, and adhesive

Figure 12: Failure Code Guide

5.0 CONCLUSIONS

This test report presents the results of testing the grade 9 titanium (Ti 3Al 2.5V) honeycomb core to relevant ASTM standards for density, plate shear, flatwise compression, flatwise tension and beam flexural properties. One of the driving forces behind this effort was that there was no published database for titanium core properties. This core was fabricated using a laser welding technology which was of strong interest because in earlier smaller studies, it was demonstrated that this core does have stronger node strength than other core fabrication technologies which should result in stronger overall core and a subsequent increase in strength-to-weight ratio.

The titanium honeycomb core applications rival aluminum in many planned aerospace/defense scenarios. As such, bare core test conclusions and comparisons will be limited, where applicable, to aluminum honeycomb core. Mechanical properties for aluminum honeycomb core do exist in the public domain and can be compared. This report does compare titanium shear properties with aluminum core shear properties.

Panel test conclusions are basically establishing the performance of the composite system. Unless the comparison is between systems with similarities, it's difficult to do anything more with the properties data than present the data. Composite systems carry different costs, performance properties, etc. The designer will choose or design a system, likely custom made, that meets his design requirements.

5.1. Density

Density will be determined by the materials and the cell geometry. In bonded core, density of the core would also include how much adhesive is used to fabricate the core. The laser welded core has no adhesives. The density dependent factors then become the ability to control the cell size and material thickness tolerance.

Material suppliers of foil, used in the production of honeycomb core, typically quote a tolerance of $\pm$10%. For this reason, Benecor normally quotes a tolerance of $\pm$10% for its core.

Benecor's tested core collectively ranged from a low of 95.6% to a high of 106.0% over the nominal density target. These measurements were taken across 6 different configurations and at least 5 blocks (or batches) of core. The conclusion is that Benecor's laser-welding technology is repeatable and produces core within the tolerance bands available for metallic foil.

5.2. Compression Testing

Compressive strength of the Benecor titanium honeycomb core was found to be very similar to published aluminum honeycomb core strength when strength and density are plotted.

This was not expected. The reported superior strength of the Benecor laser welded nodes was thought would have a noticeable impact on the compressive strength and would show an advantage over the aluminum core.

5.3. Plate Shear Testing

The plate shear testing did indicate a stronger performance, strength to weight, when compared to aluminum core. Figure 9 shows such a comparison when graphed using published aluminum core data. For the half-inch thickness performance shown in the graph, it can be estimated that there will be a 25 to 36% reduction weight for comparable strength requirements.

As was shown earlier, the shear strength in ribbon and transverse directions track together very well. When comparing the shear strengths in ribbon and transverse core orientations of Benecor's titanium core with those of aluminum core, the difference in strength between the aluminum ribbon and transverse grows with increases in density. This difference in strength by orientation will have an impact on the selection of face sheet materials and, in the case of composite face sheets, can result in less material used and a design where the impact of the core's orientation is also reduced.

5.4. Tensile Strength Properties

The tensile strength performance of the panels proved generally repeatable. This test is largely a test that reflects the strength of the bonding. The titanium core didn't tear in tension. Either the bondline between the core and face sheet failed or in a few rare cases, failure was when the face sheet split leaving part on the core and part on the tensile block. As expected, strength does increase with density. In as much as this largely represents a test of the bonding performance, thicker foil and smaller cells translate into more surface area for bonding. Higher density honeycomb core does provide more surface area than lower density.

No tensile strength testing was performed to compare zirconium coated and uncoated titanium core. The impact of that coating on tensile strength and bonding performance is unknown.

5.5. Flexural Properties

The properties are provided in the tables. Strength tended to increase with the density of the core but as the densities increased, the panels started failing before yield. Also, thicker panels were stronger than thinner at the higher densities. The impact of the face sheet strength may help account for this noticeable difference. The face sheets are balanced in layup construction.

No beam flexural strength testing to compare zirconium coated and uncoated titanium core. The impact of that coating on bonding performance and flexural strength is unknown.

6.0 RECOMMENDATIONS

This test program commenced with a very large plan to document mechanical properties. There are still roughly a dozen configurations that the aerospace industry would benefit from having available test data. These configurations include several in commercially pure titanium core as well. Benecor recommends that more testing of these materials be performed. As the testing is performed, Benecor will be updating its database for industry use. The results will be posted on Benecor's website.

The core that was tested and reported on herein was all coated using a zirconium coating that possibly enhanced the adhesive performance. That adhesion performance was not tested for coated versus uncoated core. A small representative sample of uncoated and coated core was tested for compression performance. More testing to understand the mechanism and impact of the coating is recommended.

The flexural properties in some of the testing did not exhibit the linearity required to allow for the calculation of stiffness performance parameters as required by ASTM D7250. Benecor will revisit this area of the testing and update its properties as appropriate.

The endurance characteristics of the titanium core would be of great value to the aerospace and defense application communities. It is recommended that an evaluation be performed to assess the potential impact of cyclic loading on a titanium honeycomb structure.

Thermal properties of titanium honeycomb core would be of benefit to the aerospace and military. Should such a study be funded, not only would high temperatures typical of hypersonic and reentry thermodynamics be of interest. Applications where the core forms a component of a thermal protection system for cryogenic tanks would suggest that cryogenic temperatures be considered.

It was noted that there was an expectation that compression performance would be better for the titanium core when compared against the aluminum core. If the compressive strength properties are further explored as a function of the actual (rather than nominal) density, it is possible that the compressive strength to weight ratios are different between aluminum and grade 9 titanium core.

7.0 REFERENCES

1. Bitzer, Thomas, "Honeycomb Technology: Materials, design, manufacturing, applications and testing", October 1997
2. Gaudin, Douglas, "Robust Composite Sandwich Structures (ROCSS) Program Final Report, 17 March 1995 - 12 December 2003, AFRL-VA-TR-2004-3094
3. Department of Defense, "Transition from Development to Production", DoD 4245.7-M, September 1985.
4. ASTM International, C271-05, Standard Test Method for Density of Sandwich Core Materials, April 2005.
5. Lockheed Martin/Northrop Grumman/British Aerospace Proprietary Information, "Process Specification for the Manufacture and Quality Control of JSF Non-Specific Part Family Carbon/BMI Composite Structure, 13 March 2006
6. ASTM International, C273-00, Standard Test Method for Shear Properties of Sandwich Core Materials, March 2000.
7. ASTM International, C297-04, Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions, May 2004.
8. ASTM International, C365-05, Standard Test Method for Flatwise Compressive Properties of Sandwich Cores.
9. ASTM International, C393-06, Standard Test Method for Flexural Properties of Sandwich Constructions.
10. ASTM International, D7249-06, Test Method for Facing Properties of Sandwich Properties for Long Beam Shears.
11. ASTM International, D7250-06, Standard Practice for Determining Sandwich Beam Flexural and Shear Stiffness1

8.0 GLOSSARY and ACRONYMS

Angle – In the context of testing performed for shear samples where the tensile load was applied to core 45° off the ribbon direction.

ASTM – American Society for Testing and Materials

Batch – A single production run of honeycomb core, referred to by Benecor as a block. A batch may be comprised of foil from more than one roll of foil, from one or more mill 'batches'.

Blanket – Honeycomb core that has been slabbed, pinned and stretched (expanded) to a sheet of honeycomb core

Block – A single production unit of a honeycomb batch. The block can have foil from different production rolls, different mills, but is normally of the same material and foil thickness.

BMI -- Bismaleimide

COV – Coefficient of Variation: standard deviation divided by average.

Data Volumes – Data Files

EDM – Electrical Discharge Machining: a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).

Expansion – Core orientation resulting from the stacking of ribbons which are later expanded (sometimes referred to as transverse or W-direction)

HOBE – Honeycomb before expansion

ITAR – International Traffic in Arms Regulations

JSF – Joint Strike Fighter

NDI – Non-Destructive Investigation

Ribbon – Core orientation where the foil length is continuous (sometimes referred to as L-direction)

ROCSS -- Robust Composite Sandwich Structures

Slab – A slice of HOBE removed from the welded block usually in the final desired thickness of the honeycomb blanket

Undeterminable – documentation to identify a specific item of interest could not be located for verification

WPAFB – Wright Patterson Air Force Base